AN EXERGETIC ANALYSIS OF COGENERATION PLANTS OPERATION

KOĢENERĀCIJAS STACIJU DARBĪBAS EKSERĢĒTISKĀ ANALĪZE

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Exergy can be formulated as the maximal possible job of thermodynamic system against surrounding environment, and shows the maximum limit of systems processes energy potential exploitation for useful needs. Cogeneration heat and power plants *(CHPP)* themselves are complicated thermodynamic systems, and for evaluation of plant`s operation efficiency seems every time to be obligatory an exergetic analysis [1,2] of the main thermodynamic processes of whole system. The report presented deals with an exergetic analysis of one specified cogeneration power plant operation and evaluation of eventual ways for efficiency improvement. The output figures for numerical calculations were got from public available data [3] and reports regarding *Taufkirhen* (Germany) small/middle scale cogeneration plant operation. Plant is operating with renevable biological fuel – wood waste and chips.

The basic scheme of cogeneration plant is shown on Fig.1. Here we can find out the main values and parameters of energy carrying substances and flows as well. Combustion of fuel takes place in the furnace of boiler and is producing superheated water steam finally. In its turn, produced water steam is transforming some part of steam thermal energy into mechanical energy, and in further way, electrical generator is converting some part of mechanical energy into electric one. Outflowing from turbine steam has very high energy content, and this thermal potential is used for district heating system water heating.

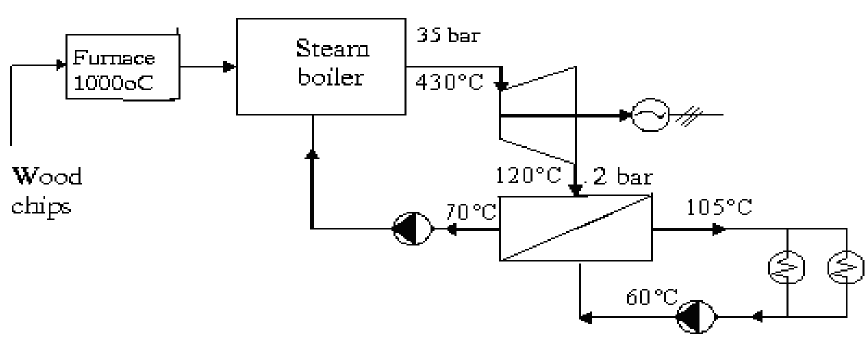

Fig.1. The basic working scheme of heat & power cogeneration plant

The superheated high pressure water steam expansion processes in steam turbine direct flow section are shown on ***h-s*** diagram (Fig.2.).

In the case of adiabatic steam expansion, we have an isoentropic process at the same time: $s_2 = s_1$.

The dryness degree index x_2 of water steam at the end of expansion proceses (with conditions $s_2 = s_1$):

$$x_2 = \frac{s_2 - s_2^{'}}{s_2^{''} - s_2^{'}} \quad (1)$$

The output data we are taking from cogeneration plant cycles characteristics, in that case, pressure of superheated steam equals to 35 *bar* , temperature $\approx 430^0 C$. Pressure of outgoing waste steam to condenser unit ≈ 2 bar, temperature of condensating steam is $120^0 C$. Enthalphy of waste steam equals to *h₁=3292 kJ/kg,* correspondingly, entrophy value is: $s_1 = s_2 = 6{,}9427 \, {kJ}/{kgK}$. Taking into account the dryness degree index value $x_2 \approx 0{,}967$ at this point, software have to calculate initial steam enthalphy h_2, as well as the theoretichal value of enthalphy difference Δh_0, real enthalphy decrease Δh_f, enthalphy losses in the turbine Δh_{zud}, temperature of steam condensation t_2 and correct value of enthalphy h_{2f} at the end fo steam expansion process. An average value of $\eta_{0i} = 0{,}9$ (various figures from producers and offered types of turbines).

Outgoing from turbine steam in practically is dry saturated steam with temperature $t_2 \approx 120^0 C$ (point 2 on the *h-s* diagram, Fig.2).

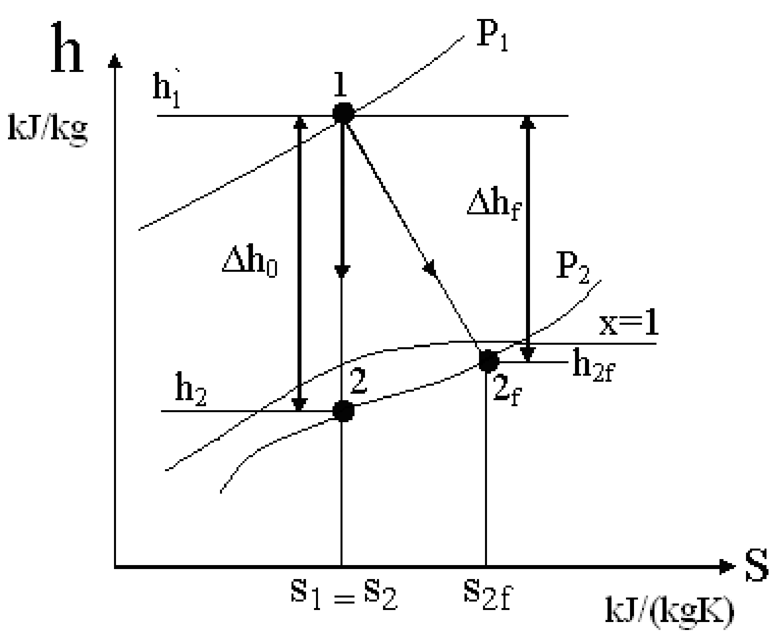

Fig.2. ***h-s*** diagram of steam expansion in the main duct part of turbine

Calculations of parameters for cycle characteristic points shows the following values of enthalphy:

$$h_2 = h_2^{'} + x_2\left(h_2^{''} - h_2^{'}\right) = 2634 \quad (kJ/kg); \qquad (2)$$

$$\Delta h_0 = h_1 - h_2 = 657{,}8 \quad (kJ/kg); \qquad (3)$$

$$\Delta h_f = 657{,}8 \cdot 0{,}9 = 592{,}02 \quad (kJ/kg); \qquad (4)$$

$$\Delta h_{zud} = \Delta h_0 - \Delta h_t = 65{,}78 \quad (kJ/kg); \qquad (5)$$

$$h_{2f} = h_2 + \Delta h_{zud} = 2700 \quad (kJ/kg)\ . \qquad (6)$$

Thermal efficiency index of steam turbine cycle:

$$\eta_{t.ef} = \frac{\Delta h_f}{h_1 - h_{bar}} = \frac{592}{3292 - 250} \approx 0{,}2\ , \qquad (7)$$

where h_{bar} – enthalphy of inlet water, *kJ/kg*.

Accounting ambient air temperature $t_0 = 20^0 C$, an exergy of superheated steam will be equal:

$$e_{D1} = q_{D1}\tau_1 = (h_1 - h_{bar})\left(\frac{T_1 - T_0}{T_1}\right) = (3292 - 251)\frac{(430+273)-(20+273)}{430+273} = 1773,\ kJ/kg; \qquad (8)$$

where:

$\tau_1 = 0{,}583$ - the exergetic temperature of superheated steam;

$$e_{D2} = q_{D2}\tau_2 = (h_2 - h_{kond})\frac{T_2 - T_0}{T_2} = (2700 - 251)\frac{402 - 297}{403} = 669,\ kJ/kg; \qquad (9)$$

$\tau_2 = 0{,}273$ - exergetic temperature of outgoing steam under conditions of nominal load, steam consumption is equal $D = 30t/h = 8{,}333$ *kg/s*, and it is assumed, then all outgoing steam is used for thermofication net water heating

An exergy of returned condensate:

$e_{kond} = q_k\tau_k = h_k\tau_k = 251 \cdot 0{,}12 = 30{,}15$ *kJ/kg*, and exergetic temperature of condensate is:

$$\tau_k = \frac{T_k - T_0}{T_k} = \frac{333 - 298}{333} = 0{,}120\ . \qquad (10)$$

Total exergetic power of cogeneration unit , (assuming $M_{D2} = M_{kond} = D$):

$$P_e = P_{el} + M_{D2}e_{D2} - M_{kond}e_{kond} = 4500 + 8{,}333 \cdot 668{,}6 - 8{,}333 \cdot 30{,}15 = 9820,\ kW. \qquad (11)$$

Consumed exergy of cogeneration P_{ep}, concerning only to the exergy of superheated steam:

$$P_{ep} = D_1 e_{D1} = Dq_1\tau_1 = D_1(h_1 - h_{bar})\frac{T_1 - T_0}{T_1} = 8{,}333 \cdot 1773 = 14774,\ kW. \qquad (12)$$

The exergetic efficiency index η_e of unit (against exergy of consumed superheated steam):

$$\eta_e = \frac{P_e}{P_p} = \frac{9820}{14774} = 0{,}665\ . \qquad (13)$$

From *Taufkirchen* cogeneration plant energy balance data [3] we can find proportion between electrical P_{el} and heating $Q_{termofik}$ power $(P_{el} = 4500(kW), Q_{termofik} = 15000(kW))$, and exergetic power of CTPP will be equal:

$$P_e = P_{el} + Q_{termofik}\tau_2 = 4500 + 1500 \cdot 0{,}273 = 8595(kW). \qquad (14)$$

Exergetic efficiency index η_e^{CHPP} of cogeneration plant, related against exergy of produced superheated steam quantity:

$$\eta_e^{CHPP} = \frac{P_e}{P_{ep}} = \frac{8595}{14774} = 0{,}582. \qquad (15)$$

At the same time, the exergetic efficiency index of cogeneration plant can be calculated against the total exergy of consumed fuel B.

Accordingly the amount of produced thermal energy, the amount of consumed fuel have to be equal to:

$$Q_{tv} = BQ_z^d \eta_{k.iek} \rightarrow B = \frac{Q_{tv}}{Q_z^d \eta_{k.iek}} \text{ kg/s}. \qquad (16)$$

Expecting energy efficiency index value of steam boiler`s unit equal to $\eta_{k.iek} = 0{,}8$, which is an average figure for such kind of equipment, we can calculate an approximate energy balance of cogeneration plant.

Amount of heat energy Q_{tv} from produced steam:

$$Q_{tv} = D(h_1 - h_{bar}) = (3292 - 251) = 25350(kW); \qquad (17)$$

and calculated consumption of fuel:

$$B = \frac{Q_{tv}}{Q_z^d \eta_{k.iek}} = \frac{25350}{12000 \cdot 0{,}8} = 2{,}641\left(\frac{kg}{s}\right). \qquad (18)$$

Exergy of fuel e_{kur} is calculated on the basis of the highest value of combustion heat $Q_A^d = 17000 \frac{kJ}{kg}$:

$$e_{kur} = Q_A^d \left(1 - \frac{W}{100}\right) = 17000(1 - 0{,}3) \approx 12000\left(\frac{kJ}{kg}\right). \qquad (19)$$

Calculated fuel consumption $b_{\bar{\imath}p}$ to produce one kilogram kg_{tv} of water steam:

$$b_{\bar{\imath}p} = \frac{B}{D} = \frac{2{,}641}{8{,}333} = 0{,}317\left(\frac{kg_{kur}}{kg_{tv}}\right). \qquad (20)$$

Exergy of consumpted fuel for 1 kg water steam production:

$$e_{kur} = b_{\bar{\imath}p.} e_{kur} = 0{,}317 \cdot 12000 = 3804\left(\frac{kJ}{kg_{tv}}\right). \qquad (21)$$

As it was calculated above, exergy of 1 kg superheated steam is equal to $e_{D1} = 1773$ *kJ/kg*.

Exergetic efficiency coefficient η_{eks} of steam boiler unit of cogeneration plant:

$$\eta_{eks} = \frac{e_{D1}}{e_{kur.pat\bar{e}a}} = \frac{1773}{3804} = 0{,}466. \qquad (22)$$

Exergetic power of consumpted fuel:

$$P_{kur} = Be_{kur} = 2{,}641 \cdot 12000 = 31692 \ kW. \quad (23)$$

Exergetic efficiency index η_{ekur} of unit in relation to exergy $P_{e.kur}$ of consumpted fuel:

$$\eta_{ekur} = \frac{p_e}{P_{e.kur}} = \frac{9820}{31692} = 0{,}310 \,. \quad (24)$$

Assuming the production balance report of *Taufkirchen* city cogeneration power plant, the total exergetic efficiency index η_{kur}^{CHPP} of plant against consumpted fuel exergy:

$$\eta_{kur}^{CHPP} = \frac{p_e^B}{P_{e.kur}} = \frac{8595}{31692} = 0{,}271. \quad (25)$$

For comparision, there are calculated values of the energetic effectiveness index for *Taufkirchen* city cogeneration power plant η_{en}^{CHPP} (total useful electric and heat energy versus the total consumed combustion heat and exergy of fuel plus heat losses):

$$\eta_{en}^{CHPP} = \frac{Q_{el} + Q_{term}}{Q_{el} + Q_{term} + Q_{zud}} = \frac{Q_{el} + Q_{term}}{BQ_z^d} = \frac{4500 + 15000}{34284} = 0{,}569 \,. \quad (26)$$

An energetic effectiveness index η_{en}^{tv} against heat amount of produced steam:

$$\eta_{en}^{tv} = \frac{Q_{el} + Q_{term}}{Q_{tv}} = \frac{4500 + 15000}{8{,}333(3292 - 251)} = 0{,}77 \,. \quad (27)$$

Conclusions

An exergetic and energetic effectiveness indexes there are determined and calculated onto data basis of technical and production reports of *Taufkirchen* city small scale heat and power cogeneration plant. Calculations were carried out at the nominal value (30 *t/h*) of steam consumption in turbine, as well as using an average input data from power plant reports for longer time of operation. Efficiency indexes in both cases were related to heat of produced steam and total combustion heat of fuel. Results obtained can be interpretted in different ways. Analysis of calculations shows values of exergetic efficiency index essentially smaller then corresponding energetic effectivity factor (coefficient of useful heat energy output).

Calculated value of energetic effectivity index (versus total heat amount of fuel combustion) is $\eta_{en} = 0{,}57$, at the same time value of exergetic effectivity index in corresponding conditions is equal to $\eta_e^{KHPP} = 0{,}27$. That shows quite low degree of thermal energy potential use in given technological scheme and working conditions.

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Nagla J., Turlajs D., Grivcovs V., Jaundālders S. Koģenerācijas staciju darbības ekserģētiskā analīze

Darbā izstrādāta reāli darbojošās nelielas jaudas koģenerācijas iekārtas darbības eksergētiskās analīzes metodika un dots iekārtas termodinamisko procesu efektivitātes novērtējums. Aprēķinu izejas dati iegūti no koģenerācijas termoelektrostacijas darba režīmu un ekonomisko rādītāju ilgtermiņa pārskatiem. Aprēķini parāda, ka, attiecinot efektivitāti uz sadedzinātā kurināmā siltumu, enerģētiskais lietderības koeficients (siltuma izmantošanas koeficients) ir divas reizes lielāks par atbilstošo eksergētisko lietderības koeficienta vērtību (attiecīgi 57% un 27%). Tas, savukārt, norāda uz teorētiskām iespējām atrast metodes efektīvākai kurināmā siltuma enerģijas izmantošanai. Metodes izmantošana var dot reālu ieguldījumu komplicētu enerģētisko sistēmu projektēšanā un darbības optimizācijā.

Nagla J., Turlajs D., Grivcovs V., Yaundalders S. An Exergetic Analysis of Cogeneration Plant Operation

An exergetic method of really existing cogeneration heat and power plant operation analysis is elaborated and plant`s thermodynamic processes effectiveness evaluation is presented in the given report. Power plant`s technical and economical report for a long time of operation period was used for numerical efficiency indexes evaluation. Numerical calculations shows twice as high value of the total thermal efficiency index (related to the total combustion heat of consumed fuel) against the exergetic efficiency index (57% and 27% correspondingly). That lets to think regarding theoretical possibilities to find methods for more efficient application of combustion heat. The method of an exergetic analysis will give certain contribution for designing and efficiency optimization of complicated heat & power systems.

Нагла Я., Турлайс Д., Гривцов В., Яундалдерс С. Эксергетический анализ работы когенераторных установок

В статье разработан метод эксергетического анализа действующей когенераторной установки для производства теплоты и электроэнергии и представлена оценка эфективности деествия установки с термодинамической точки зрения. Для расчета использованы исходные данные из технического и экономического отчета о работе данной КТЭС за длительный период времени. Численные расчёты показали, что общий термический коэффициент (в отношении к теплоте сгорания использованного топлива) полезного действия в два раза выше эксергетического коэффициента (57% и 27% соответственно). Это, в свою очередь, заставляет думать о поиске методов максимально эффектиной реализации энергии топлива. Использование метода внесет реальный вклад в проектирование сложных энергетических систем и оптимизации их работы.